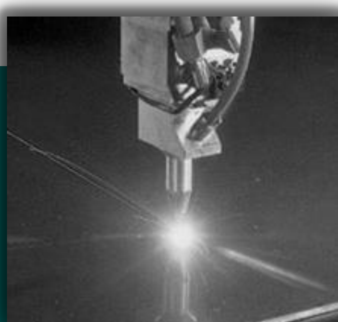
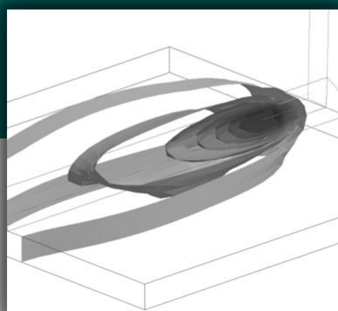
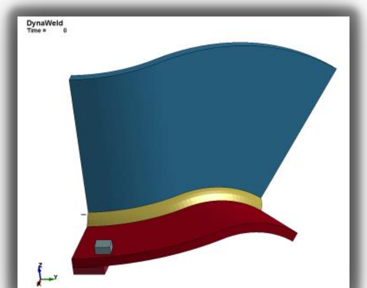


Welding Simulations with LS-DYNA

- Recent Developments-



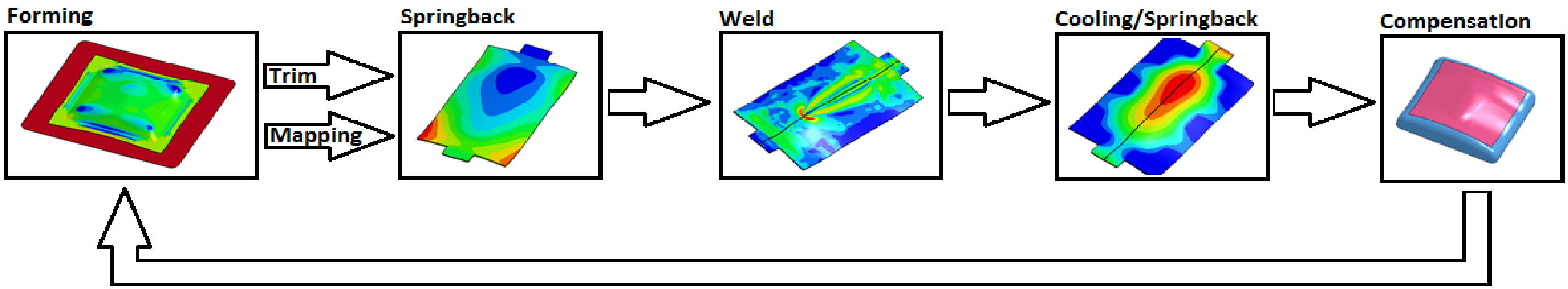


Dr.-Ing. Thomas Klöppel

DYNAmore GmbH

Simulation of the manufacturing process chain

- For modern processes and materials, the mechanical properties of the finished part highly depend on the fabrication chain
- Tooling has to be compensated for springback and shape distortions which occur in the fabrication chain



- Numerical simulations of the complete process chain necessary to predict finished geometry and properties
- The individual stages pose very different requirements on the numerical solver

Recent development topics

- Realistic description of the heat source applied to the weld seam
  - For curved geometries
  - For deforming structures (thermal expansion during welding)
  - Heat sources with power density distribution other than Goldak
  - COMBINATIONS OF THE ABOVE

- Microstructure evolution within the material
  - Phases changes due to heating and cooling
  - Transformations induce strains, plasticity, change in mechanical properties and thermal porperties
  - Valid description for a wide range of steel and aluminium alloys

- How to deal with application without additional material in the welded zone?

Goldak Double Ellipsoid heat source

- Double ellipsoidal power density distribution proposed in [Goldak2005]

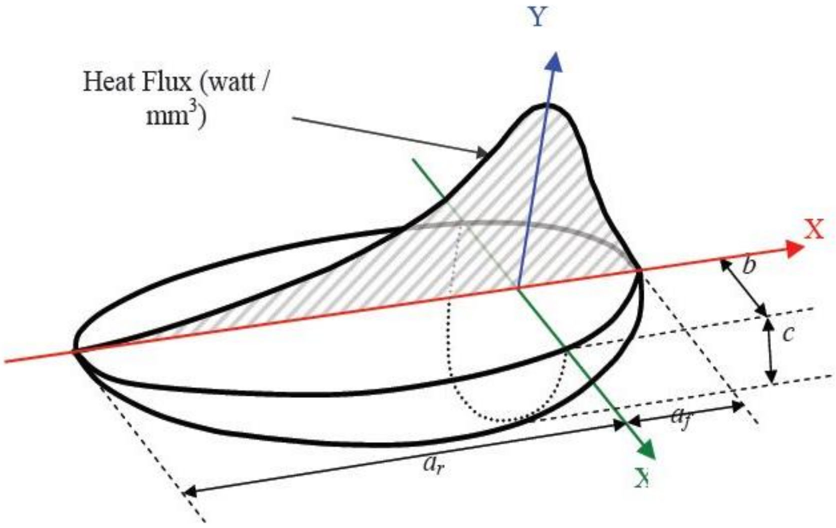
$$q = \frac{6\sqrt{3}FQ}{\pi\sqrt{\pi}abc}\exp\left(\frac{-3x^2}{a^2}\right)\exp\left(\frac{-3y^2}{b^2}\right)\exp\left(\frac{-3z^2}{c^2}\right)$$

q = weld source power density

(x, y, z) = coordinates of point p in weld material

$$F = \begin{cases} F_f \text{ if point } p \text{ is in front of beam} \\ F_r \text{ if point } p \text{ is behind beam} \end{cases}$$

$$c = \begin{cases} c_f \text{ if point } p \text{ is in front of beam} \\ c_r \text{ if point } p \text{ is behind beam} \end{cases}$$

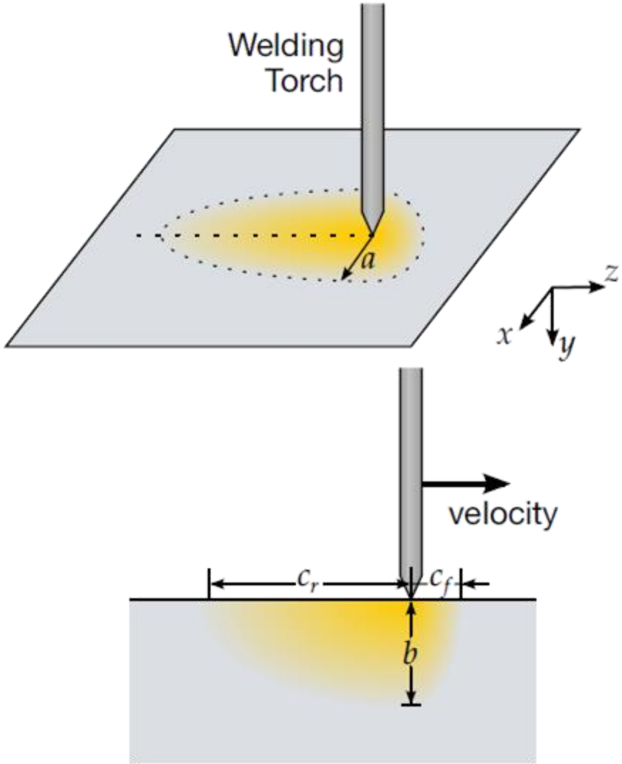


- Most widely used for industrial applications
- Can be defined in LS-DYNA using keyword *BOUNDARY_THERMAL_WELD

*BOUNDARY_THERMAL_WELD

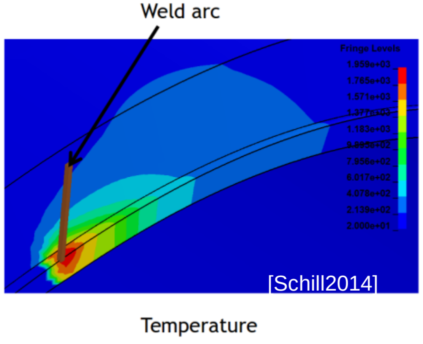
	1	2	3	4	5	6	7	8
Card 1	PID	PTYP	NID	NFLAG	X0	Y0	Z0	N2ID
Card 2	a	b	cf	cr	LCID	Q	Ff	Fr
Opt.	Tx	Ty	Tz					

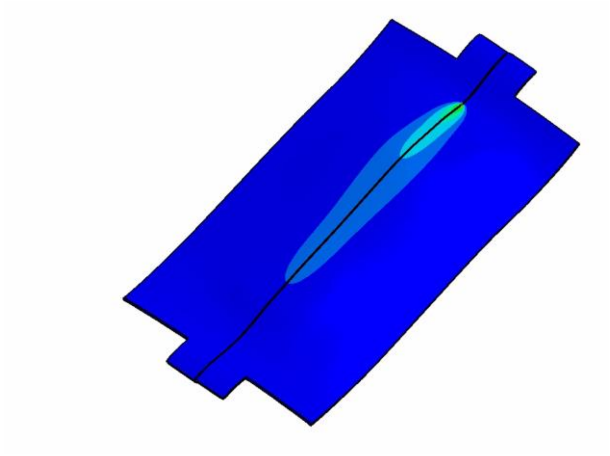
- NID: Node ID giving the location of weld source
- NFLAG: Flag controlling motion of source
  EQ.1: source moves with node
  EQ.0: fixed in space
- N2ID: Second node ID for weld beam direction
  GT.0: beam is aimed from N2ID to NID
  EQ.-1: beam aiming direction is (Tx, Ty, Tz)

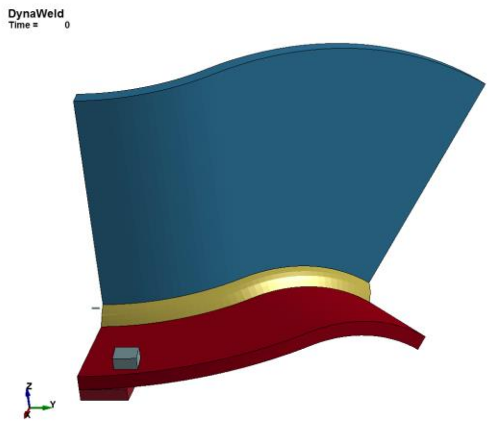


Movement of the heat source 1

- Beam motion (e.g. *BOUNDARY_PRESCRIBED_MOTION_RIGID) allows defining the translation and rotation of the heat source
- For previously deformed or curved structures, the description of the heat source is NOT straight-forward
- Movement of the part has to be compensated for







Movement of the heat source 2

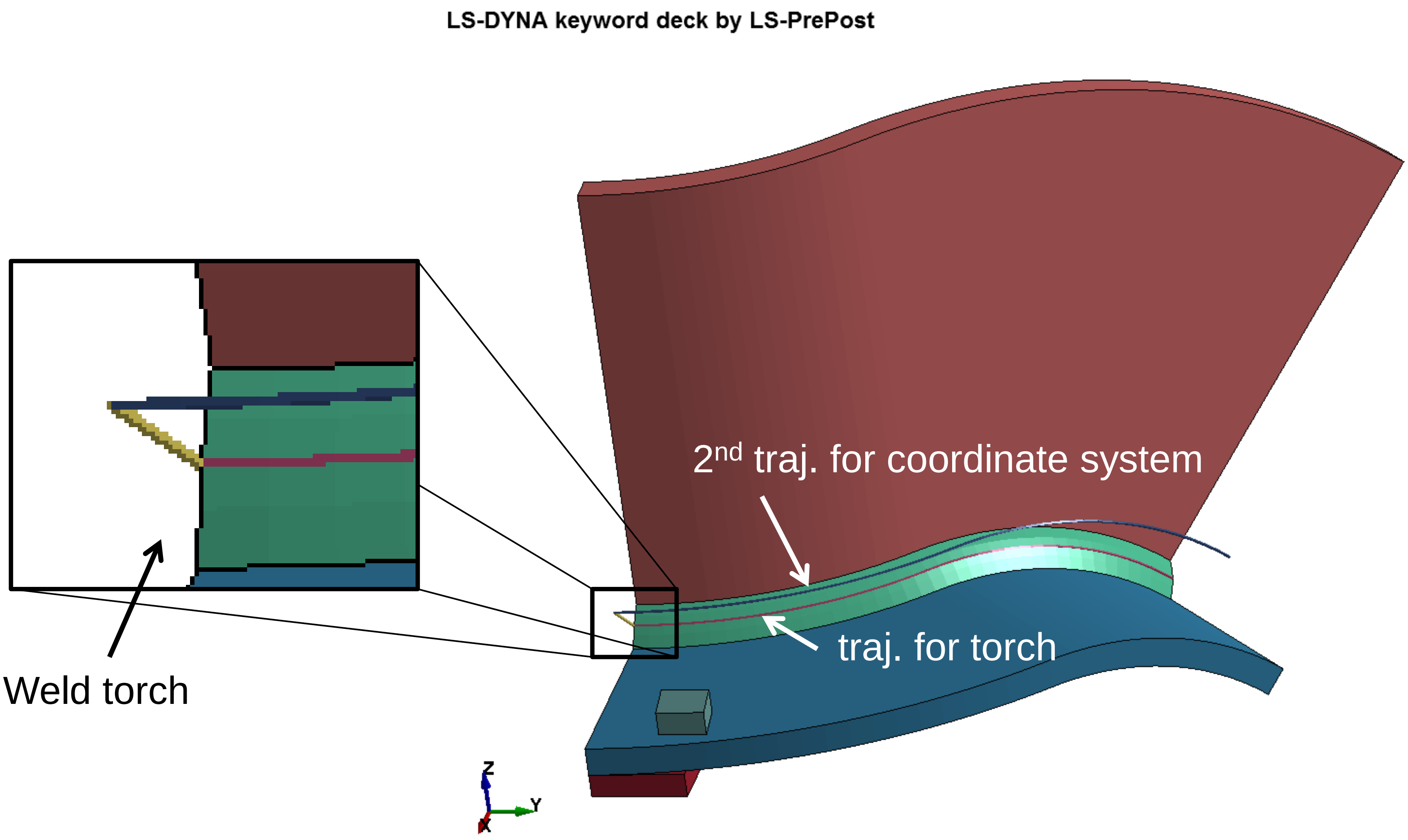
- Useful keyword: *CONTACT_GUIDED_CABLE

	1	2	3	4	5	6	7	8
Card 1	NSID	PID	CMULT	WBLCID	CBLCID	TBLCID		

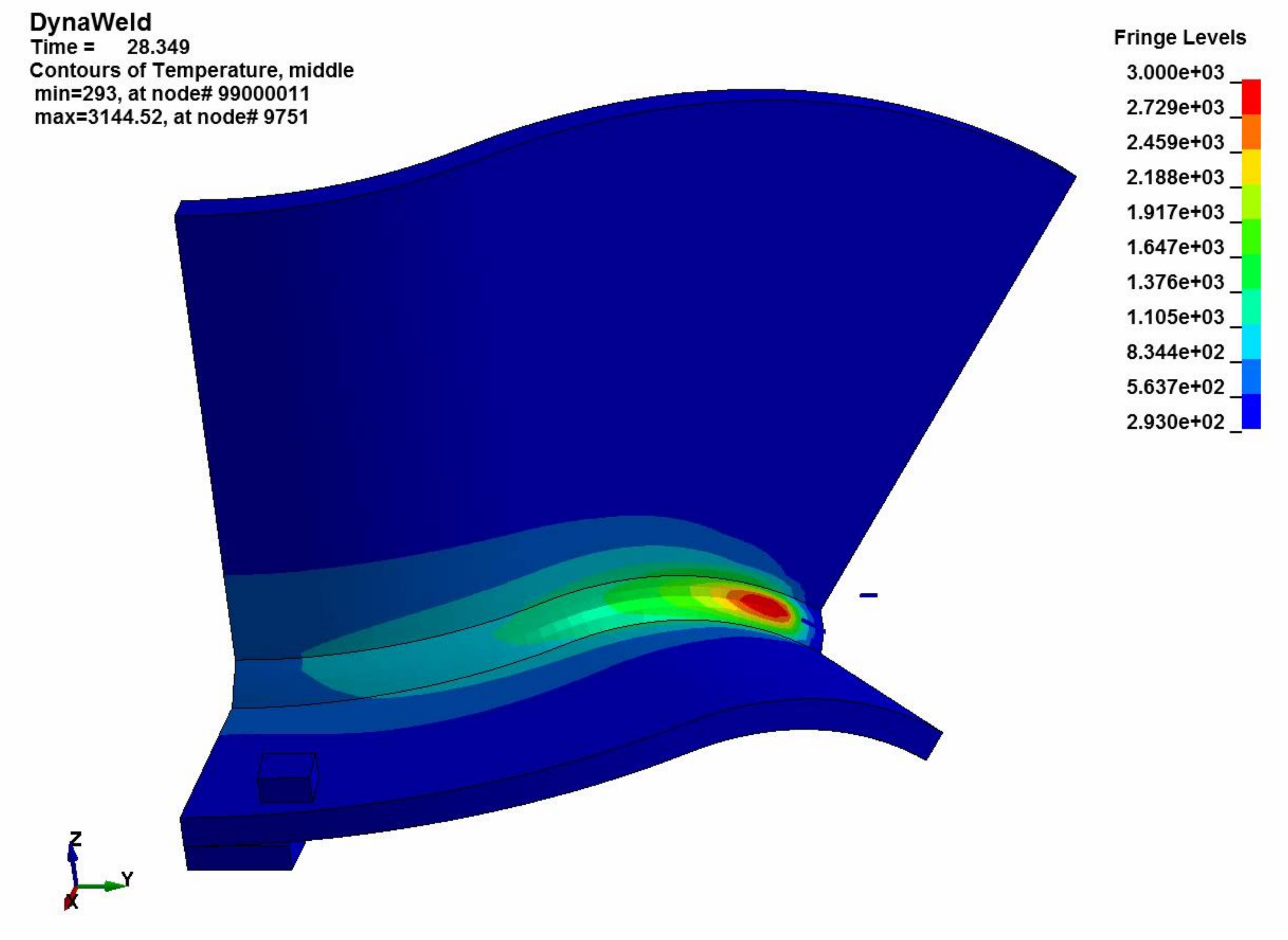
  - It forces beams in PID onto the trajectory defined by nodes in NSID

- Possible solution
  - Select a trajectory on the weld seam
  - Define contact between this trajectory and a beam B1 (N1 and N2)
  - Define a second trajectory and a beam B2 (N3 and N4) following it in a prescribed manner
  - Welding torch aiming directions from N3 to N1 (*BOUNDARY_THERMAL_WELD)
  - Define local coordinate system N1,N2,N3
  - Use *BOUNDARY_PRESCRIBED_MOTION_RIGID_LOCAL to move heat source

Movement of the heat source - example

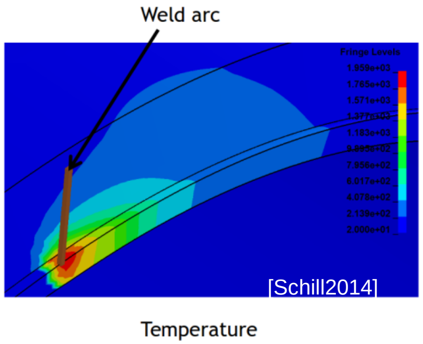


Movement of the heat source - example



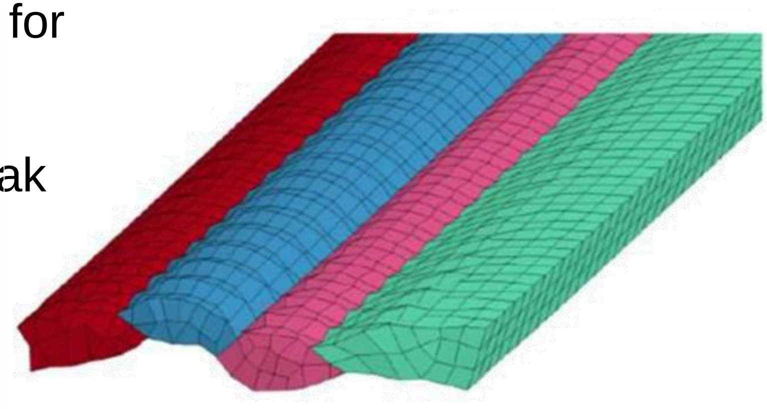
Movement of the heat source

- Beam motion (e.g. *BOUNDARY_PRESCRIBED_MOTION_RIGID) allows defining the translation and rotation of the heat source



- For previously deformed or curved structures, the description of the heat source is NOT straight-forward

- Movement of the part has to be compensated for



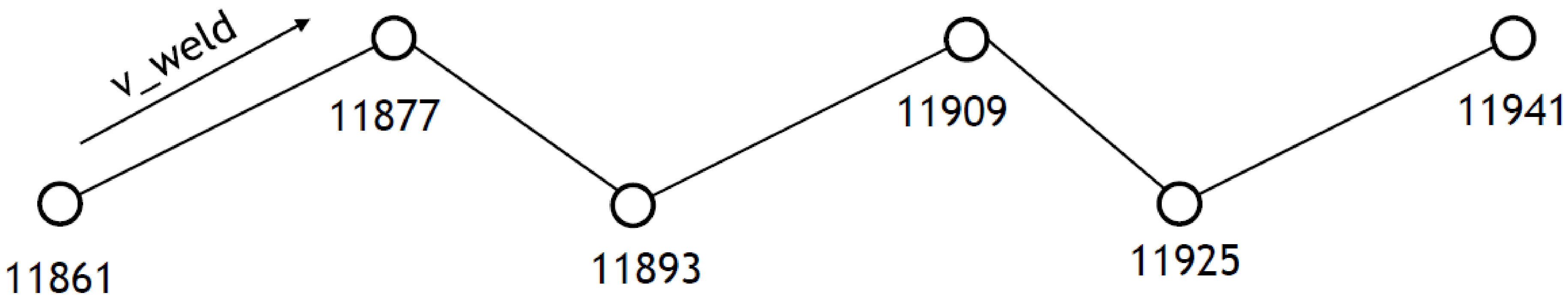
- The incremental heating when using the Goldak heat source leads to element distortion when a too large timestep is used.

- The mechanical solver is needed to move the heat source even though this should be solvable using only the thermal solver.

A new heat source - Approach

- Move the heat source movement to a new keyword.
- The heat source follows a prescribed velocity along a node path (*SET_NODE)
- The weldpath is continuously updated
- No need to include the mechanical solver

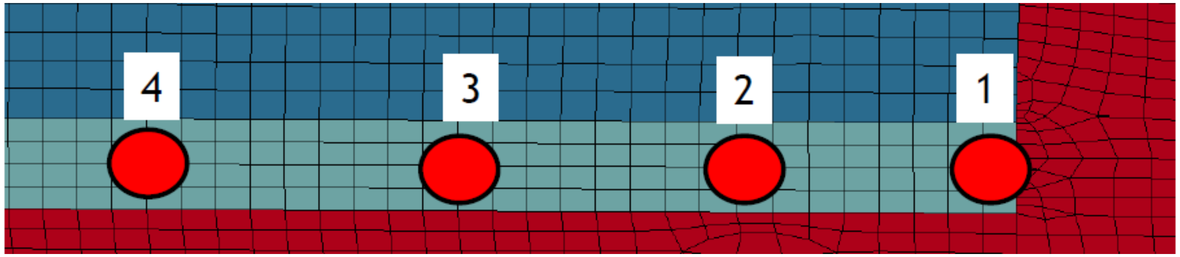
```
*SET_NODE_LIST
1
11861,11877,11893,11909,11925,11941
```



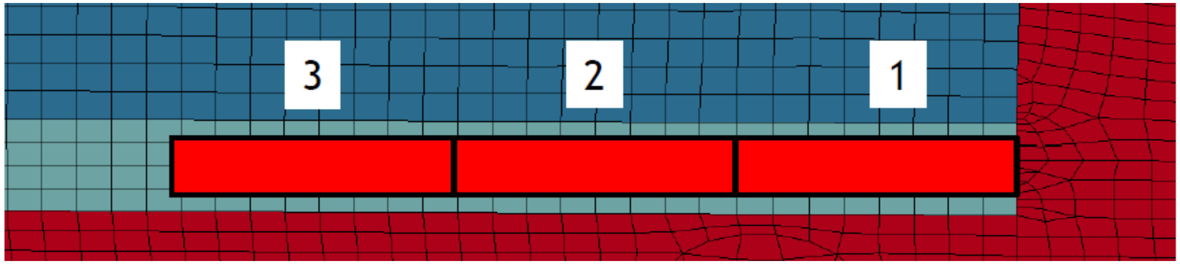
A new heat source - Approach

- Move the heat source movement to new keyword.
- The heat source follows a prescribed velocity along a nodepath
- The weldpath is continuously updated
- No need to include the mechanical solver
- Use “sub-timestep” for integration of heat source

Weld source evaluated at thermal timesteps



Weld source integrated between thermal time steps



*BOUNDARY_THERMAL_WELD_TRAJECTORY

	1	2	3	4	5	6	7	8
Card 1	PID	PTYP	NSID1	VEL1	SID2	VEL2	NCYC	
Card 2	IFORM	LCID	Q	LCROT	LCMOV	LCLAT	DISC	
Card 3	P1	P2	P3	P4	P5	P6	P7	P8
Opt.	Tx	Ty	Tz					

- NSID1: Node set ID defining the trajectory
- VEL1: Velocity of weld source on trajectory
  - LT.0: |VEL1| is load curve ID for velocity vs. time
- SID2: Second set ID for weld beam direction
  - GT.0: S2ID is node set ID, beam is aimed from these reference nodes to trajectory
  - EQ.0: beam aiming direction is (Tx, Ty, Tz)
  - LT.0: SID2 is segment set ID, weld source is orthogonal to the segments
- VEL2: Velocity of reference point for SID2.GT.0
- NCYC: number of sub-cycling steps

*BOUNDARY_THERMAL_WELD_TRAJECTORY

	1	2	3	4	5	6	7	8
Card 1	PID	PTYP	NSID1	VEL1	SID2	VEL2	NCYC	
Card 2	IFORM	LCID	Q	LCROT	LCMOV	LCLAT	DISC	
Card 3	P1	P2	P3	P4	P5	P6	P7	P8
Opt.	Tx	Ty	Tz					

- IFORM: Geometry for energy rate density distribution
  - EQ.1. Goldak-type heat source
  - EQ.2. double ellipsoidal heata source with constant density
  - EQ.3. double conical heat source with constant density
  - EQ.4. conical heat source

*BOUNDARY_THERMAL_WELD_TRAJECTORY

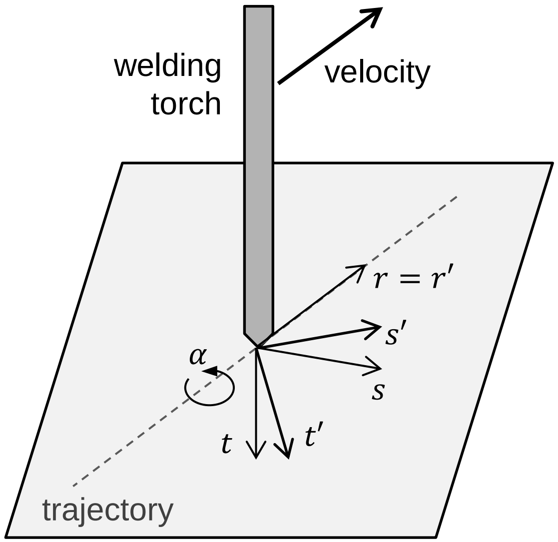
	1	2	3	4	5	6	7	8
Card 1	PID	PTYP	NSID1	VEL1	SID2	VEL2	NCYC	
Card 2	IFORM	LCID	Q	LCROT	LCMOV	LCLAT	DISC	
Card 3	P1	P2	P3	P4	P5	P6	P7	P8
Opt.	Tx	Ty	Tz					

- LCID: Load curve ID for weld energy input rate vs. time
  - EQ.0: use constant multiplier value Q
- Q: Curve multiplier for weld energy input
  - LT.0: use absolute value and accurate integration of heat
- DISC: Resolution for accurate integration. Edge length for cubic integration cells
  - Default: 0.05*(weld source depth)

*BOUNDARY_THERMAL_WELD_TRAJECTORY

	1	2	3	4	5	6	7	8
Card 1	PID	PTYP	NSID1	VEL1	SID2	VEL2	NCYC	
Card 2	IFORM	LCID	Q	LCROT	LCMOV	LCLAT	DISC	
Card 3	P1	P2	P3	P4	P5	P6	P7	P8
Opt.	Tx	Ty	Tz					

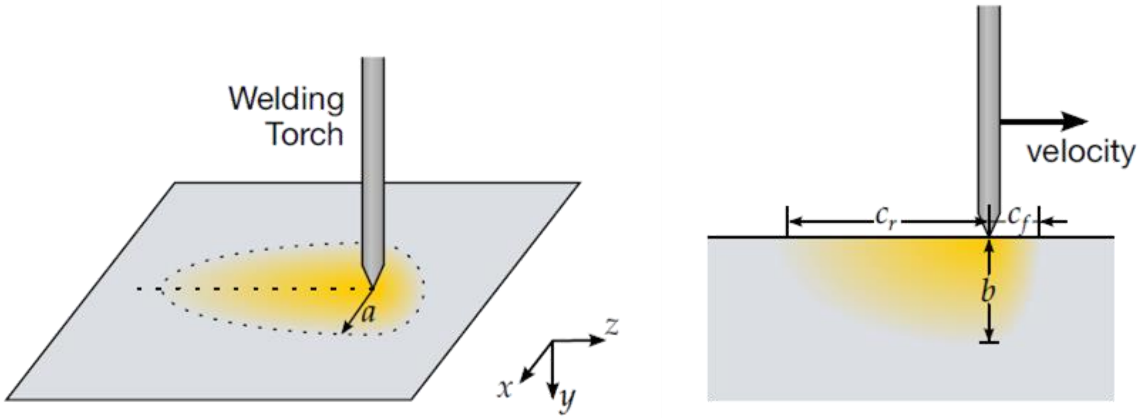
- LCROT: load curve defining the rotation (α in degree) of weld source around the trajectory as function of time.
- LCMOV: load curve for offset of weld source in depth (t') after rotation as funtion of time
- LCLAT: load curve for lateral offset (s') after rotation as function of time



*BOUNDARY_THERMAL_WELD_TRAJECTORY

	1	2	3	4	5	6	7	8
Card 1	PID	PTYP	NSID1	VEL1	SID2	VEL2	NCYC	
Card 2	IFORM	LCID	Q	LCROT	LCMOV	LCLAT	DISC	
Card 3	P1	P2	P3	P4	P5	P6	P7	P8
Opt.	Tx	Ty	Tz					

- For IFORM=1
  - P1: a
  - P2: b
  - P3: c_f
  - P4: c_r
  - P5: F_f
  - P6: F_r
  - P7: n

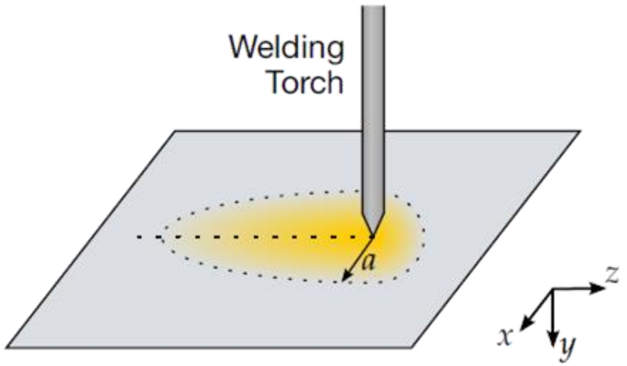


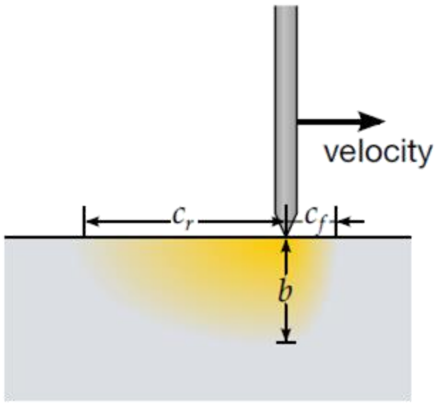
$$q = \frac{2n\sqrt{n}FQ}{\pi\sqrt{\pi}abc} \exp\left(\frac{-nx^2}{a^2}\right) \exp\left(\frac{-ny^2}{b^2}\right) \exp\left(\frac{-nz^2}{c^2}\right)$$

*BOUNDARY_THERMAL_WELD_TRAJECTORY

	1	2	3	4	5	6	7	8
Card 1	PID	PTYP	NSID1	VEL1	SID2	VEL2	NCYC	
Card 2	IFORM	LCID	Q	LCROT	LCMOV	LCLAT	DISC	
Card 3	P1	P2	P3	P4	P5	P6	P7	P8
Opt.	Tx	Ty	Tz					

- For IFORM=2
  - P1: a
  - P2: b
  - P3: c_f
  - P4: c_r
  - P5: F_f
  - P6: F_r



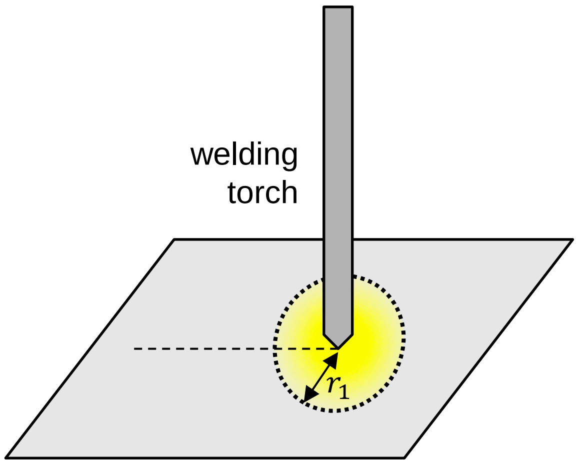


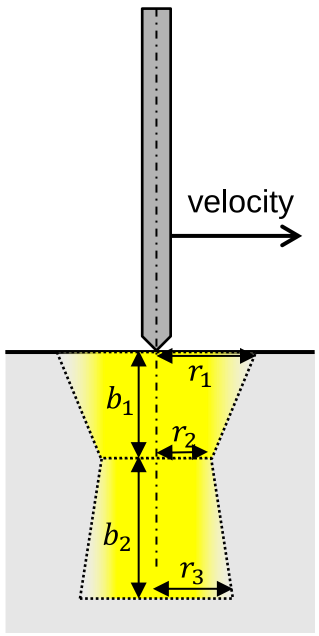
$$q = \frac{3F}{2\pi abc}$$

*BOUNDARY_THERMAL_WELD_TRAJECTORY

	1	2	3	4	5	6	7	8
Card 1	PID	PTYP	NSID1	VEL1	SID2	VEL2	NCYC	
Card 2	IFORM	LCID	Q	LCROT	LCMOV	LCLAT	DISC	
Card 3	P1	P2	P3	P4	P5	P6	P7	P8
Opt.	Tx	Ty	Tz					

- For IFORM=3
  - P1: r_1
  - P2: r_2
  - P3: r_3
  - P4: b_1
  - P5: b_2
  - P6: F_1
  - P7: F_2



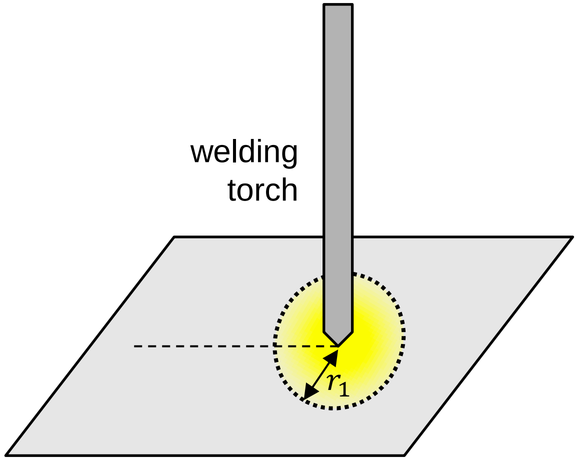


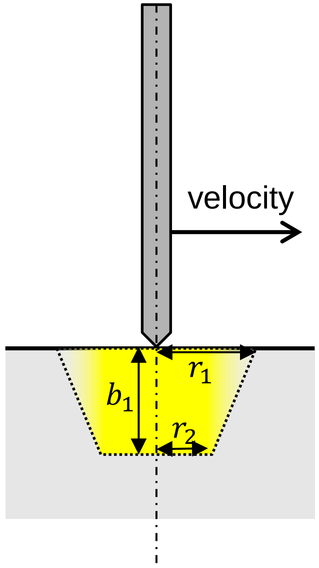
$$q = \frac{3F}{2\pi b(R^2 + r^2 + Rr)}$$

*BOUNDARY_THERMAL_WELD_TRAJECTORY

	1	2	3	4	5	6	7	8
Card 1	PID	PTYP	NSID1	VEL1	SID2	VEL2	NCYC	
Card 2	IFORM	LCID	Q	LCROT	LCMOV	LCLAT	DISC	
Card 3	P1	P2	P3	P4	P5	P6	P7	P8
Opt.	Tx	Ty	Tz					

- For IFORM=4
  - P1: r_1
  - P2: r_2
  - P3: b_1

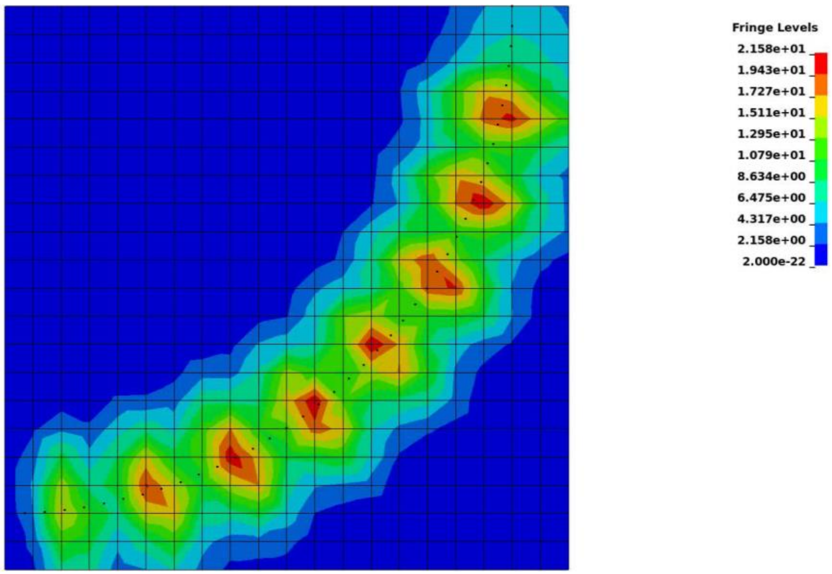




$$q = \frac{3}{\pi b(R^2 + r^2 + Rr)}$$

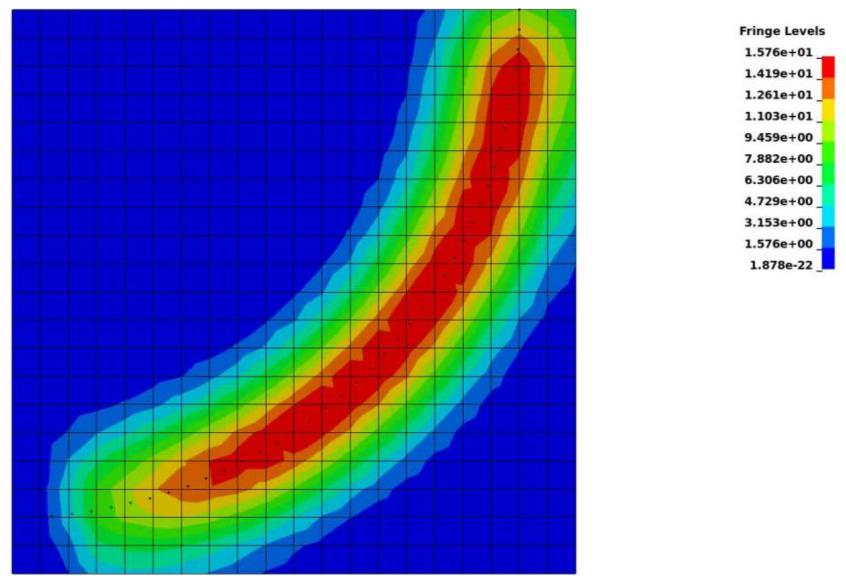
Example

- Welding on a circular trajectory
  - Thermal-only analysis with a large time step



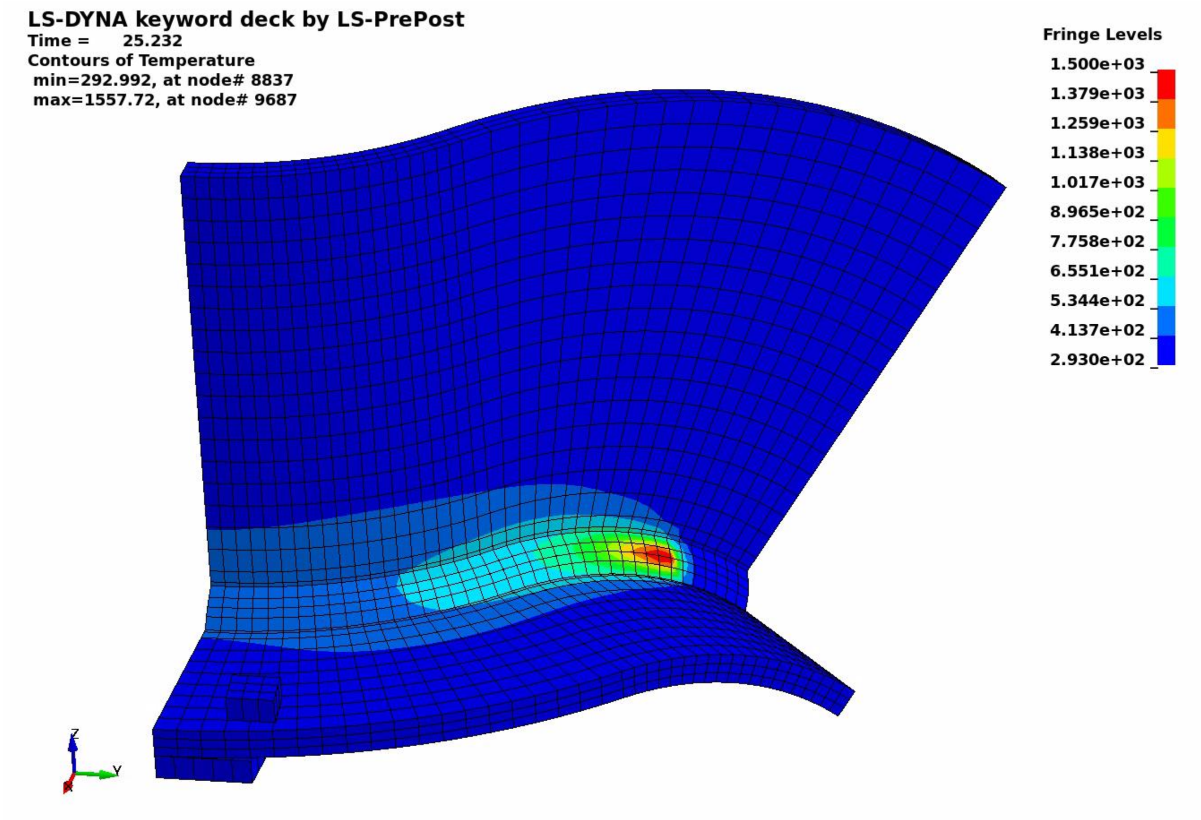
temperature field, NCYC = 1

temperature field, NCYC = 10



Example

- Welding of a three-dimensionally curved T-Joint
  - Coupled analysis
  - Weld source direction defined with a segment set



Recent development topics

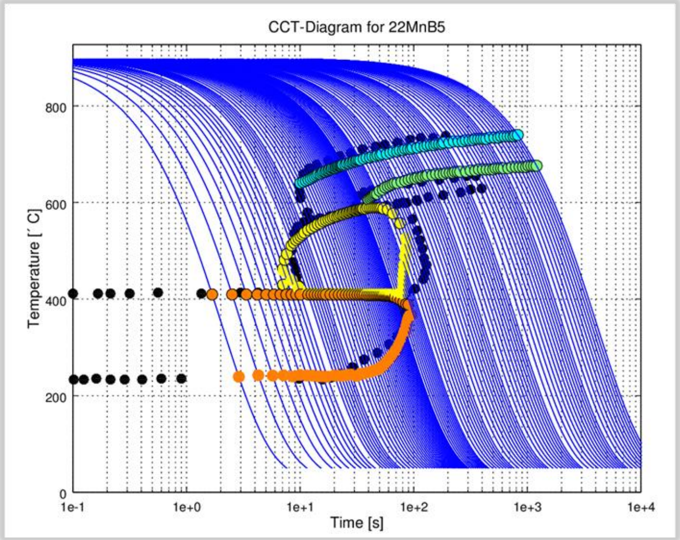
- Realistic description of the heat source applied to the weld seam
  - For curved geometries
  - For deforming structures (thermal expansion during welding)
  - Heat sources with power density distribution other than Goldak
  - COMBINATIONS OF THE ABOVE

- Microstructure evolution within the material
  - Phases changes due to heating and cooling
  - Transformations induce strains, plasticity, change in mechanical properties and thermal porperties
  - Valid description for a wide range of steel and aluminium alloys

- How to deal with application without additional material in the welded zone?

*MAT_UHS_STEEL/*MAT_244 - Basis

- Material tailored for hot stamping / press hardening processes
  - Phase transition of austenite into ferrite, pearlite, bainite and martensite for cooling
  - Strain rate dependent thermo-elasto-plastic properties defined for individual phases
  - Transformation induced plasticity algorithm
  - Re-austenitization during heating
  - User input for microstructure computations is chemical composition alone



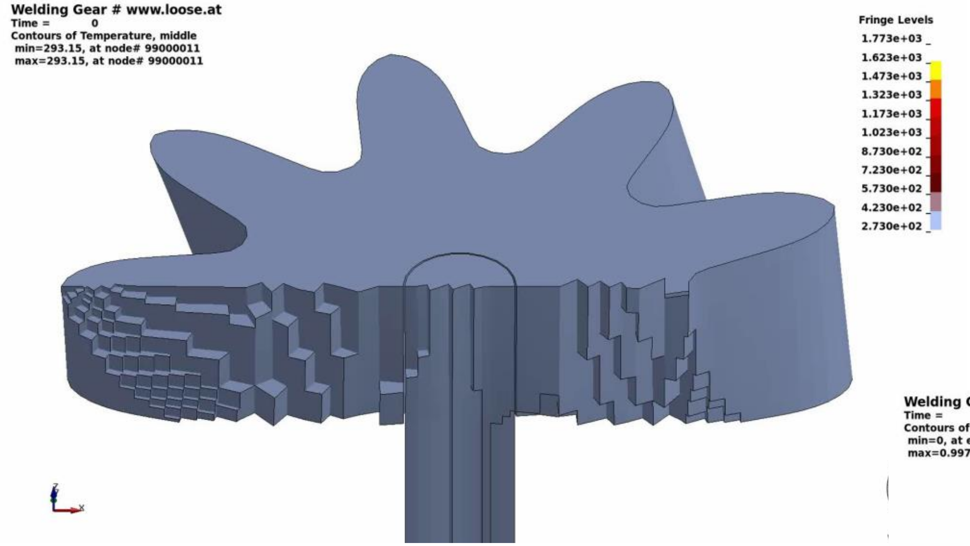
- Added:
  - Transformation induced strains
  - Welding functionality
  - Different transformation start temperatures for heating and for cooling

***MAT_244 is only valid for a narrow range of steel alloys!**

Heuristic formulas connecting chemistry with mechanics fail otherwise!

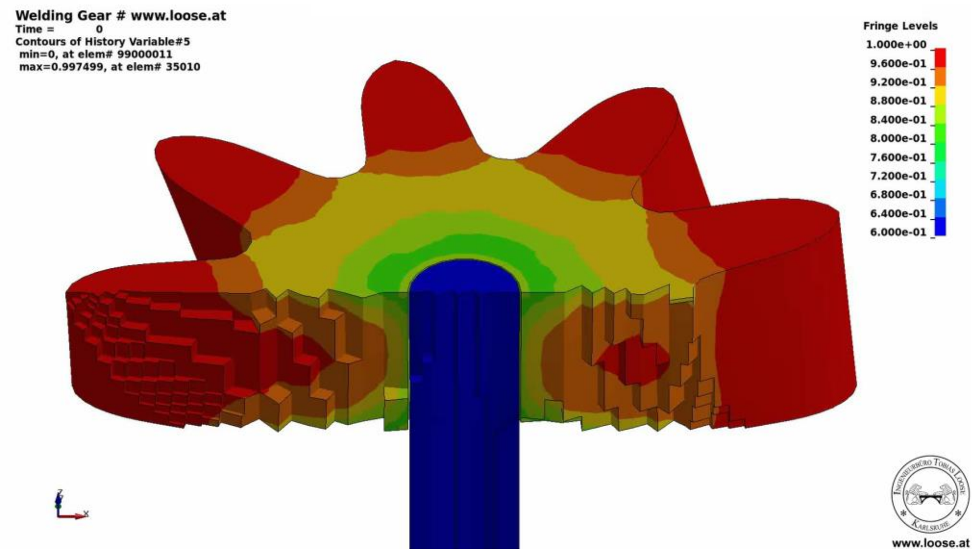
Example

- A gear is heated, quenched, welded to a joint



Temperature field

Martensite concentration



*MAT_254

- Started the implementation of *MAT_GENERALZE_PHASE_CHANGE
- Features
  - Up to 24 individual phases
  - User can choose from generic phase change mechanisms (Leblond, JMAK, Koistinen-Marburger,…) for each possible phase change
  - Material will incorporate all features of *MAT_244
  - Phase change parameters are given in tables and are not computed by chemical composition
- Will be suitable for a wider range of steel alloys and aluminum alloys
- Parameter of the material might come from a material database or a microstructure calculation

*MAT_254 / *MAT_GENERALIZED_PHASE_CHANGE

	1	2	3	4	5	6	7	8
Card 1	MID	RHO	N	E	PR	MIX	MIXR	BETA
Card 2	TASTART	TAEND	TABCTE	EPSDA0	EPSFAIL	FAILMIX	DTEMP	TIME
Card 3	PTLAW	PTSTR	PTEND	PTX1	PTX2	PTX3	PTX4	PTX5
Card 4	PTTAB1	PTTAB2	PTTAB3	PTTAB4	PTTAB5			
Card 5	PTEPS	TRIP	PTHEAT	PTPLAS	PTDAM	GRAI		
Card 6	LCY1	LCY2	LCY3	LCY4	LCY5	LCY6	LCY7	LCY8
Card 7	LCY9	LCY10	LCY11	LCY12	LCY13	LCY14	LCY15	LCY16
Card 8	LCY17	LCY18	LCY19	LCY20	LCY21	LCY22	LCY23	LCY24

- Special welding card not needed. Liquid filler can be accounted for by an additional phase

- Damage and failure modelling, latent heat, grain growth modelling yet to be implemented

*MAT_254 / *MAT_GENERALIZED_PHASE_CHANGE

	1	2	3	4	5	6	7	8
Card 1	MID	RHO	N	E	PR	MIX	MIXR	BETA

- N: Number of phases in microstructure
- E: Young’s modulus
  - LT.0: |E| is load curve ID/table ID for E vs. temperature (vs. phase)
- PR: Poissons’s ratio
  - LT.0: |E| is load curve ID/table ID for PR vs. temperature (vs. phase)
- MIX: Load curve ID for initial phase concentrations
- MIXR: LC / TAB ID for mixing rule (temperature dependent)

*MAT_254 / *MAT_GENERALIZED_PHASE_CHANGE

	1	2	3	4	5	6	7	8
Card 2	TASTART	TAEND	TABCTE	EPSDA0	EPSFAIL	FAILMIX	DTEMP	TIME

- TASTART: Annealing start temperature
- TAEND: Annealing end temperature
- TABCTE: coefficient of thermal expansion (CTE)
  - LT.0: |TABCTE| is load curve ID/table ID for CTE vs. temperature (vs. phase)
- DTEMP: Maximum temperature variation within a time step
- TIME: time scale

*MAT_254 / *MAT_GENERALIZED_PHASE_CHANGE

	1	2	3	4	5	6	7	8
Card 3	PTLAW	PTSTR	PTEND	PTX1	PTX2	PTX3	PTX4	PTX5
Card 4	PTTAB1	PTTAB2	PTTAB3	PTTAB4	PTTAB5			

- PTLAW: Table ID containing phase transformation laws
  - If law ID.GT.0: used for cooling
  - If law ID.LT.0: used for heating
  - |LAW ID|:
    - EQ.1: Koistinen-Marburger
    - EQ.2: JMAK
    - EQ.3: Kirkaldy (only cooling)
    - EQ.4: Oddy (only heating)
- PTSTR: Table ID containing start temperatures
- PTEND: Table ID containing end temperature
- PTX*i*: *i*-th scalar parameter (2D table input)
- PTTAB*i*: *i*-th temperature dependent parameter (3D table input)

*MAT_254 / *MAT_GENERALIZED_PHASE_CHANGE

	1	2	3	4	5	6	7	8
Card 3	PTLAW	PTSTR	PTEND	PTX1	PTX2	PTX3	PTX4	PTX5
Card 4	PTTAB1	PTTAB2	PTTAB3	PTTAB4	PTTAB5			

- Koistinen Marburger:
  - Evolution equation:

$$x_b = x_a\left(1.0 - e^{-\alpha(T_{start}-T)}\right)$$

  - Parameter:
    - PTX1: α

*MAT_254 / *MAT_GENERALIZED_PHASE_CHANGE

	1	2	3	4	5	6	7	8
Card 3	PTLAW	PTSTR	PTEND	PTX1	PTX2	PTX3	PTX4	PTX5
Card 4	PTTAB1	PTTAB2	PTTAB3	PTTAB4	PTTAB5			

- Johnson-Mehl-Avrami-Kolmogorov (JMAK):
  - Evolution equation:

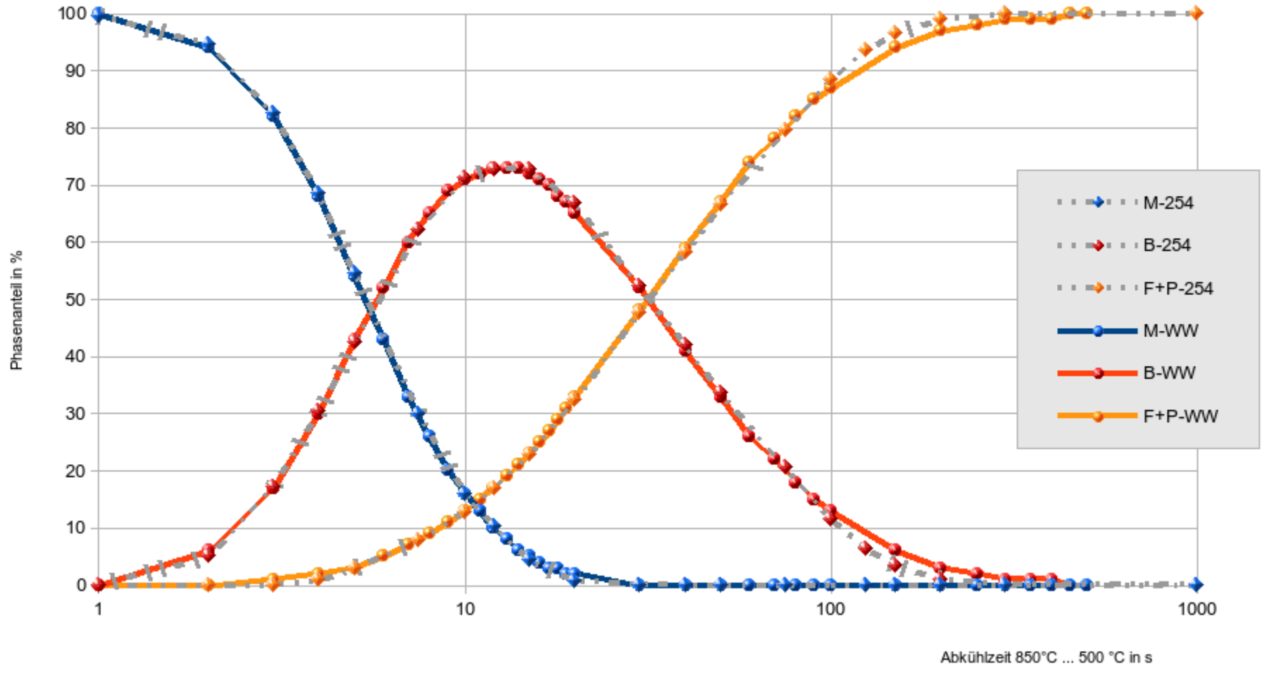
$$\frac{dx_b}{dt} = n(T)(k_{ab}x_a - k'_{ab}x_b)\left(\ln\left(\frac{k_{ab}(x_a + x_b)}{k_{ab}x_a - k'_{ab}x_b}\right)\right)^{\frac{n(T)-1.0}{n(T)}}$$

$$k_{ab} = \frac{x_{eq}(T)}{\tau(T)} f(\dot{T}), k'_{ab} = \frac{1.0 - x_{eq}(T)}{\tau(T)} f'(\dot{T})$$

  - Parameter:
    - PTTAB1: $n(T)$
    - PTTAB2: $x_{eq}(T)$
    - PTTAB3: $\tau(T)$
    - PTTAB4: $f(\dot{T})$
    - PTTAB5: $f'(\dot{T})$

*MAT_254 with JMAK

- First example: Phase change test for steel S420



*MAT_254 / *MAT_GENERALIZED_PHASE_CHANGE

	1	2	3	4	5	6	7	8
Card 3	PTLAW	PTSTR	PTEND	PTX1	PTX2	PTX3	PTX4	PTX5
Card 4	PTTAB1	PTTAB2	PTTAB3	PTTAB4	PTTAB5			

- Kirkaldy (equivalent to *MAT_244):
  - Evolution equation:

$$\frac{dX_b}{dt} = 2^{0.5(G-1)} f(C)(T_{start} - T)^{n_T} D(T) \frac{X_b^{n_1(1.0-X_b)}(1.0 - X_b)^{n_2 X_b}}{\mathrm{Y}(X_b)}, x_b = X_b x_{eq}(T)$$

  - Parameter:
    - PTX1: $f(C)$
    - PTX2: n_T
    - PTX3: n_1
    - PTX4: n_2
    - PTTAB1: $\mathrm{D}(T)$
    - PTTAB2: $\mathrm{Y}(X_b)$
    - PTTAB3: $x_{eq}(T)$

*MAT_254 / *MAT_GENERALIZED_PHASE_CHANGE

	1	2	3	4	5	6	7	8
Card 3	PTLAW	PTSTR	PTEND	PTX1	PTX2	PTX3	PTX4	PTX5
Card 4	PTTAB1	PTTAB2	PTTAB3	PTTAB4	PTTAB5			

- Oddy (equivalent to *MAT_244):
  - Evolution equation:

$$\frac{dx_b}{dt} = n \cdot \frac{x_a}{c_1(T - T_{start})^{-c_2}} \cdot \left(\ln\left(\frac{(x_a + x_b)}{x_a}\right)\right)^{\frac{n-1.0}{n}}$$

  - Parameter:
    - PTX1: n
    - PTX2: c_1
    - PTX3: c_2

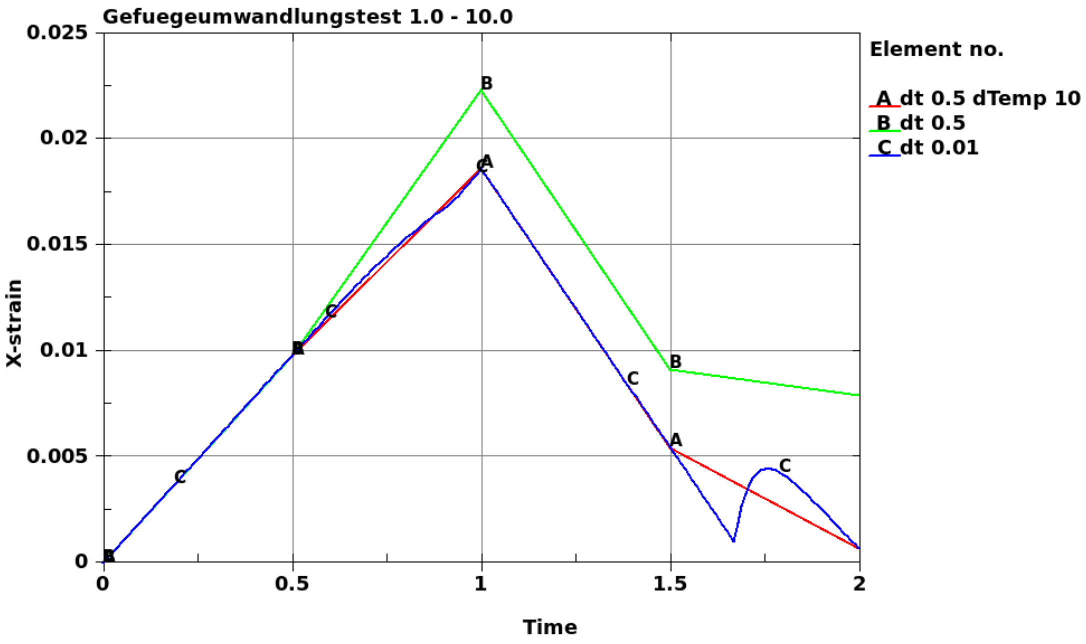
*MAT_254 / *MAT_GENERALIZED_PHASE_CHANGE

	1	2	3	4	5	6	7	8
Card 5	PTEPS	TRIP	PTHEAT	PTPLAS	PTDAM	GRAI		

- PTEPS: Table ID for transformation induced strains
- TRIP: Flag for transformation induced plasticity (active for TRIP.gt.0)
- GRAIN: Initial grain size

Effect of DTEMP

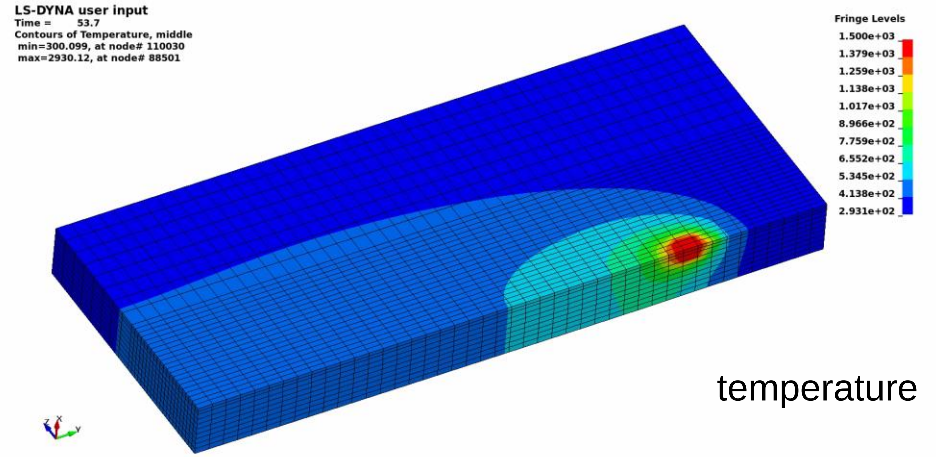
- Rapid heating and cooling of a single element
- Non-linear strains as transformation induced strains and the coefficient of thermal expansion depend on the temperature



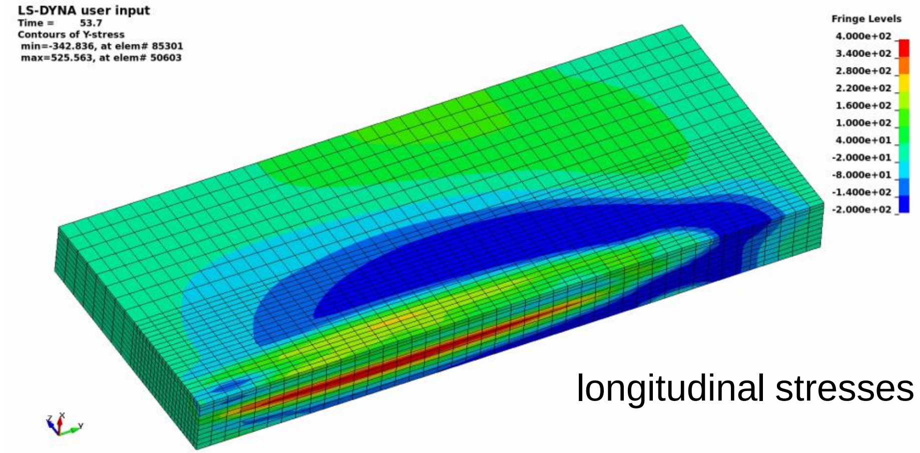
- Results for small time steps can be reproduced if DTEMP is sufficiently small

Residual stresses

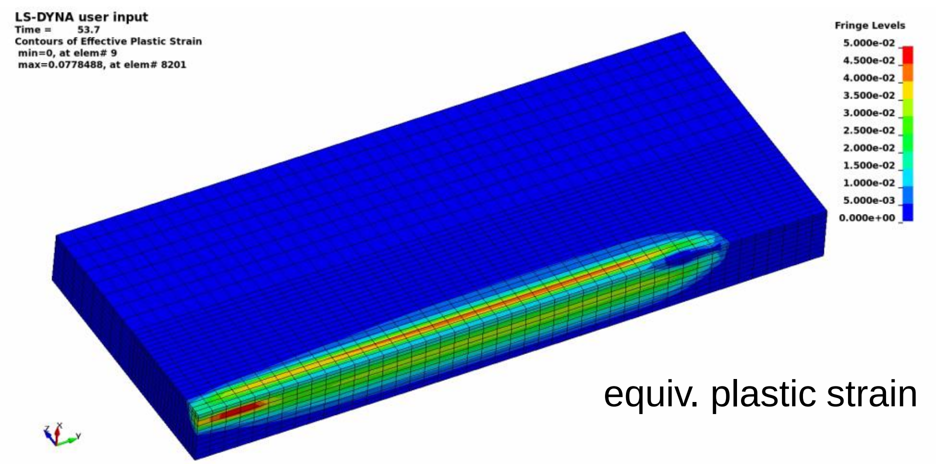
- Nitschke-Pagel test



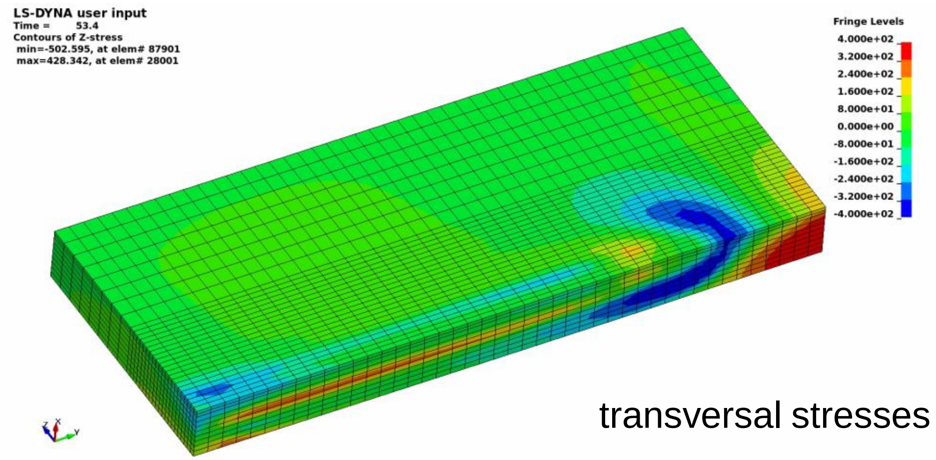
temperature



longitudinal stresses



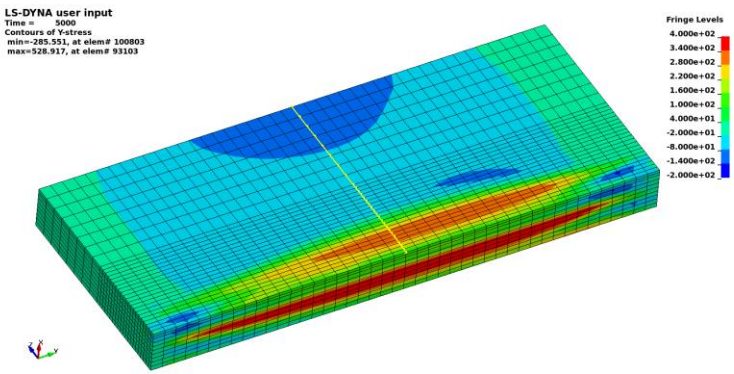
equiv. plastic strain

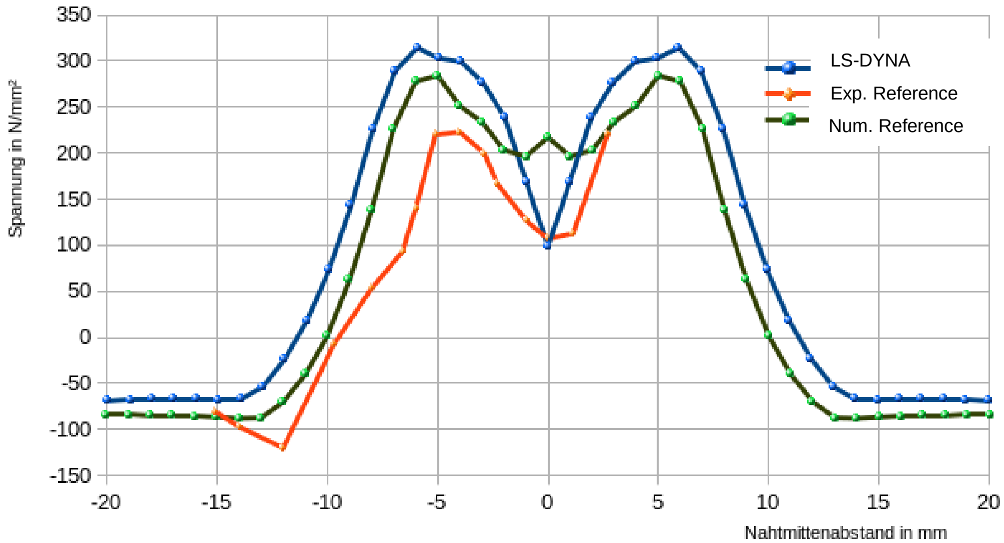


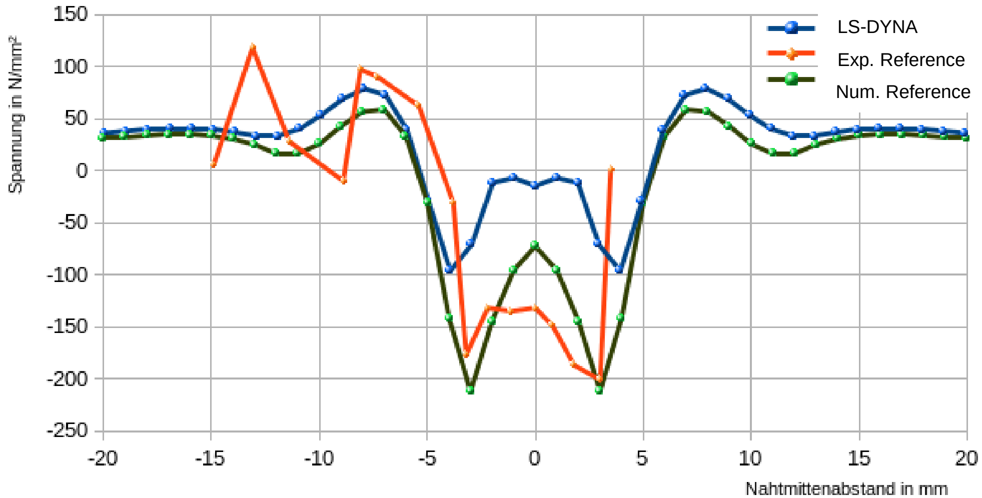
transversal stresses

Residual stresses

- Nitschke-Pagel test







Recent development topics

- Realistic description of the heat source applied to the weld seam
  - For curved geometries
  - For deforming structures (thermal expansion during welding)
  - Heat sources with power density distribution other than Goldak
  - COMBINATIONS OF THE ABOVE

- Microstructure evolution within the material
  - Phases changes due to heating and cooling
  - Transformations induce strains, plasticity, change in mechanical properties and thermal porperties
  - Valid description for a wide range of steel and aluminium alloys

- How to deal with application without additional material in the welded zone?

Welding without filler elements

- Ghost element approach is not suitable for all welding processes
  - No material might be added in the process
  - Significant sliding of parts before welding

- New contact formulation *CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_TIED_WELD_THERMAL
  - As regions of the surfaces are heated to the welding temperature and come into contact, the nodes are tied
  - Regions in which the temperature in the contact surface is always below the welding temperature, standard sliding contact is assumed
  - Heat transfer in the welded contact zones differs as compared to unwelded regions

  - Right now, only implemented for contact between solid elements, but Dave Benson is working on a shell to shell version right now

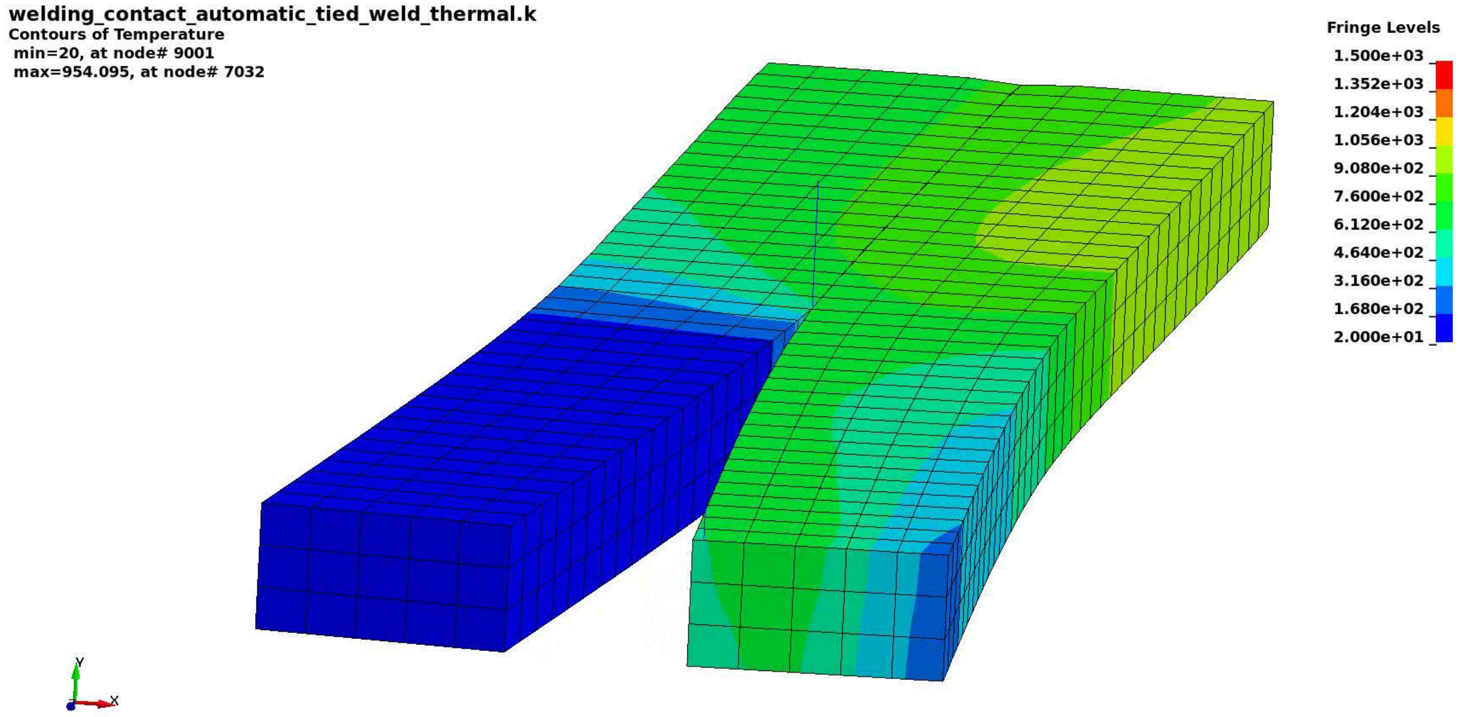
*CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_TIED_WELD_THERMAL

	1	2	3	4	5	6	7	8
Card 4	**TEMP**	**CLOSE**	**HWELD**					
Card 5	K	Hrad	**H0**	LMIN	LMAX	CHLM	BC_FLAG	1_WAY

- Card4 is read if TIED_WELD is set
  - TEMP: Welding temperature
  - CLOSE: maximum contact gap for which tying is considered
  - HWELD: Heat transfer coefficient for welded regions
- Card5 is standard for THERMAL option
  - H0: Heat transfer coefficient for unwelded regions

*CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_TIED_WELD_THERMAL

- Example: butt weld
  - During welding the blocks are allowed to move
  - Assumption: Insulation in unwelded state, perfect heat transfer after welding



Thank you!